APPLICATION NOTE:

USING LONG TETHERS FOR DC POWER TRANSMISSION

EXECUTIVE SUMMARY

DC links can be classified as being either physically static or mobile. A static system might be installed in a commercial building campus or on a piece of gear set in a remote site, such as on a mountain. Motion-based systems include aerial drones, remote controlled underwater vehicles, and robots.

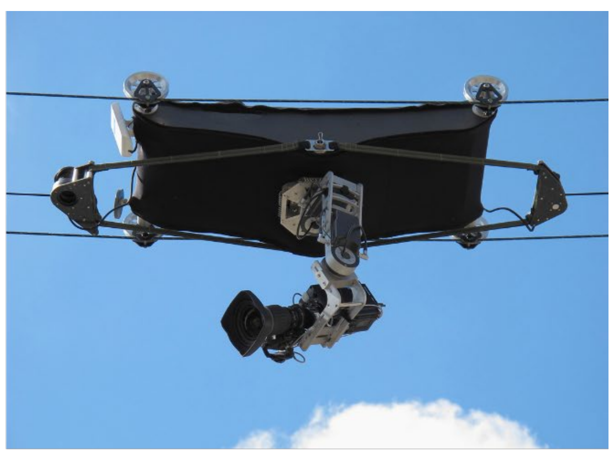
The aim of this article is to help engineers identify and resolve operational problems on DC links using practical methods and accessible design aids.

INTRODUCTION

The practice of using long tethers for DC power transmission requires special scrutiny. The number of applications involving long DC links warrants an examination of methods of coping with the cable's ability to store and redistribute energy under dynamic conditions.

TETHER LIMITATIONS FOR POWER TRANSMISSION

The designers of appliances that require tethers come up against physical limitations, particularly when they must move around. In the case of aerial or underwater unmanned vehicles, the tether applies weight and friction forces to its "working end," where the electronics package is connected. The ability of an inspection robot to move through a narrow pipe or opening when it performs operations in constricted or hazardous spaces depends primarily on the nature of this payload's tether. A heavy linkage offers more inertia and friction and the increased possibility of being snared as it passes obstacles. It can also weigh down a drone in flight continuously, and this effect can worsen if there are prevailing winds. Both kinds of drag reduce flight time. Thinner, lightweight tethers with reinforced jacketing relieve physical constraints on the "package" that is drawing power from such cordage.



HIGH VOLTAGE DC POWER TETHERS

While either AC or DC distribution voltage may be considered, direct current is not hindered by AC skin effect, which reduces the available cross-section of the cable for transporting power. Additionally, DC power generally results in simpler voltage reduction converters at the payload end of the tether.

The freedom to increase DC transmission voltage at a given level of power transfer between a DC source and a load reduces the limitations on tether length otherwise imposed by conductor cross-section and its associated weight. Cost also goes down with smaller diameter conductors. These reductions occur because current draw reduces inversely with increasing applied DC voltage for a given amount of power transfer.

Power supplies that provide the right combination of high voltages and multi-kW power levels prove to be the best choice for sourcing large amounts of DC power in the more demanding tether-based applications.

HIGH POWER SYSTEM DESIGNS

Innovations in high power system design at Astrodyne TDI follow customer demand seen in critical industrial, communications, and defense sectors. These markets require higher levels of power throughput capability at increased DC output voltages.

It is not surprising to find long lines being operated in the 800V DC range and beyond, delivering 20 kW or more to the remote DC load.

To make for cost-effective approaches to resolve such power challenges, Astrodyne TDI produces both modular and specialty systems. Both standard and custom approaches allow the development of high-quality solutions, with bespoke options introduced to apply new features that meet customers' special requirements.

Astrodyne TDI Standard Product Offerings to Support Tether Front-End Power

In the Liquablade family, modules are rated at 16.5 kW in a 1U profile. The AC front end and DC-DC converter subsystems are liquid-cooled. Voltage denominations offered are 48V DC fixed and adjustable, ranging up to 60V, 120V, 180V, and 500V DC. These hot-pluggable units are interfaced with shelves and vertically stacked in 19" racks for realizing series and parallel output-configured solutions. Liquacore solutions provide smaller power denominations which feature the use of modules originally developed for Liquablade products.

Standard 2U high power supplies in the Mercury Flex family can also have output ports arrayed in parallel and series combinations. A shelf can accommodate multiple Mercury Flex "rectifiers," each delivering 3.8 kW up to a maximum of 15.2 kW, i.e 4 paralleled modules. In an example application, 900V DC at 7 kW is required. This output voltage is realized by using series connected 450V DC rated module pairs using a customized shelf. Other output voltage denominations are also available.

If the deployment involves the use of power levels beyond the 16.5 kW "outer marker" encountered with the Liquablade, other solutions are available to meet those needs. For example, with the HV PowerNode range of industrial power supplies, a 4U power shelf offers solutions that can be made from 22.5 kW output capable 4U high shelves in 150V, 250V, and 450V DC voltage ranges.

All the high-power architectures deploy voltage droop-set current sharing. This facilitates power balance in arrays of such unit elements in shelves that can be stacked vertically in a 19" cabinet, supporting power levels to 100kW or higher. The power supply modules have inbuilt series power output diodes to prevent back-feeding of their individual output power ports. This permits controlled startup and maximum runtime.

Often, there is a need for a customized power solution. The Astrodyne TDI engineering group routinely develops power-dense solutions that have competitive cost metrics associated with total cost of ownership, power delivery, and weight.

High-power offerings beyond 1 kW that are developed and manufactured by Astrodyne TDI are complemented with extensive filter solutions and an exhaustive catalog of low power DC products in the 5W to 1 kW range.

DESIGNING A POWER SYSTEM WITH LONG TETHERS

Many requests for engineering assistance are directed to the applications teams during the project design and debug phases.

Power converters that work fine when running from a lab power supply or a LISN (line impedance stabilization network) terminated DC source can display undesirable effects when a tether is implemented. It can be awkward to arrange a long cable in the lab setting. The tether might be stowed on a reel, possibly affecting its properties. Such a system is set up to fail during the commissioning phase after the source and load are set on each end of the deployed tether. Including the effects of transients on the power distribution system shown in **Figure 1** is a critical objective.

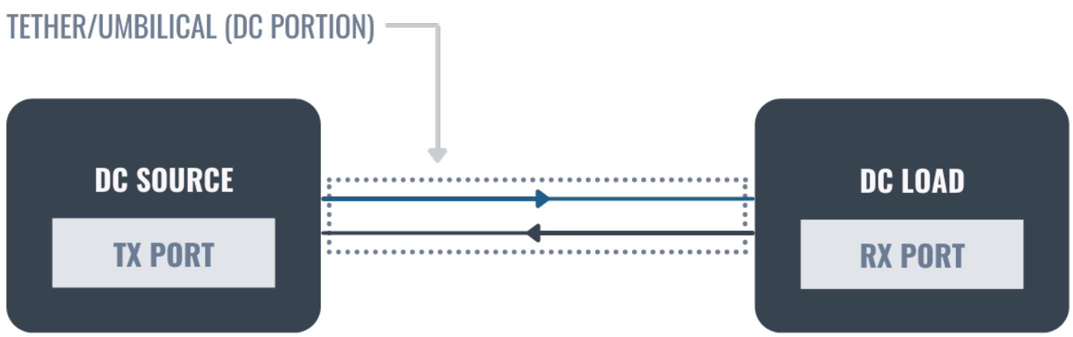


Figure 1 – block diagram of system powered with DC tether. Red and black conductor arrows indicate conventional DC current flowing in a loop between source and load.

Let's consider applying input voltage to the unpowered tether at the transmitter end using a switch. As the switch closes, one can expect a step increase in voltage at switch closure, resulting in a short rise time in the voltage measured at the "sender" (TX) port. With a very short rise time in relation to the cable's propagation delay, you should expect to see some surprising effects at the "receiver" or RX port. In certain situations, adverse outcomes result from rapid changes in the load as well as the source.

DC TRANSMISSION TETHER MODEL EXAMPLES

Shifting from modelling a DC distribution cable as resistor to that of a circuit with memory, in short, delay, is key to finding the cable's likely response to transients applied to it. Two examples are described which allow the reader to frame and work the kinks out of the system.

The first example uses an LE (lumped-element) model to introduce time-domain modelling of the power distribution arrangement. The second example introduces a

TL (transmission line) model alongside its LE counterpart and a frequency-domain view of things. Showing similarities and differences in the outcomes of the use of the 2 different tether models informs readers about the facility of each model.

FIRST APPLICATION· A LEARNING EXPERIENCE

A customer had technical questions about a 120W regulator mounted on an evaluation test fixture. It had been properly configured using jumpers on the board to program a constant current output of 2A over the part's adjustable output voltage range of 36V to 54V.

The customer wanted "protection" to account for the use of a small lead-acid battery stack to power this fixture. I had noted from the regulator's datasheet that it could operate with DC input voltages within the 21V to 75V range. Regulators were failing once they were connected to this battery-powered source.

I asked how the regulator was being connected to the battery, as it wasn't obvious why there would be a 100V peak voltage coming from a DC battery with terminal voltage of 56V. The battery was supported by a portable gantry. It was connected to an array of LED panels through a 10m long pair of DC conductors. Two attempts at turn-on and the subsequent unexplained failures had brought the project to a halt.

TIME DOMAIN MODELING

The regulator has delay and soft-start features built-in. As such, it can be modelled as a delayed constant current source with a relatively slow rise time. There is a passive filter fitted on the test fixture to control EMI noise. The twinned 16 AWG wire pair cable is represented with discrete passive components. The transient simulation model and outcome are shown in **Figure 2** at the point in time when the connection at TX is made between the battery (modeled as a zero-impedance voltage source) and the cable.

On making the DC connection, the output port {reg_in} of the dormant regulator rings-up severely. This is a facsimile of the suspected OV transient. Note that there is a very short delay between the establishment of the voltage at the TX port and voltage appearing at the RX end of the tether due to the presence of the LC networks making up the cable as well as the test fixture filter. The regulator is represented as a simple open circuit, as it hasn't started up at this point in simulated time. If there is significant internal capacitance, this will appear in parallel with C3.

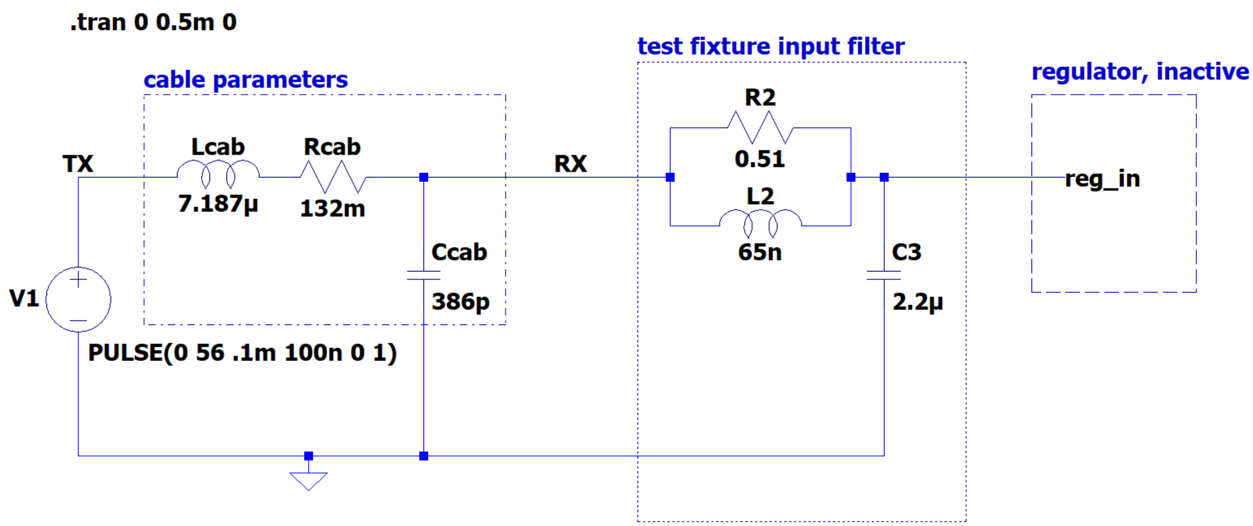


Figure 2(a) – time domain simulation schematic for cable gantry simulation at turn-on.

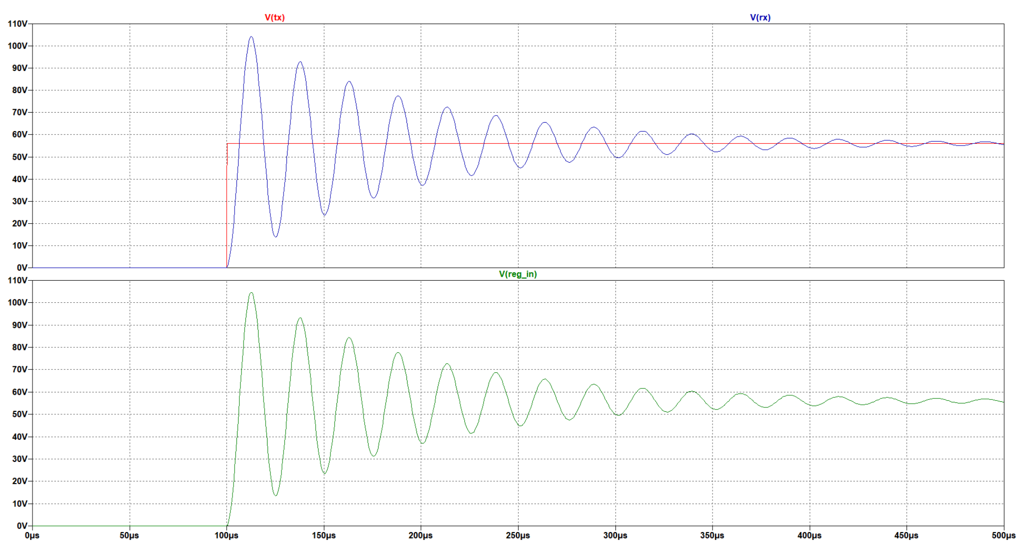


Figure 2(b) – outcome of the time domain simulation of the lighting gantry showing the input overvoltage event.

Oscillograms of the voltages at the RX and reg_in ports indicate that the filter {L2, R2, C3} has little effect on this damped 39.3 kHz oscillation. The pole associated with the test fixture's filter is set close to 349 kHz. Attenuating this transient involved adding a capacitor C1 at the RX node, adding a new 10 kHz pole. This frequency was selected to be lower than the regulator's control bandwidth of 18 kHz.

With natural resonant frequency ω0 [radians/sec] expressed in terms of cable inductance and added capacitance

$$(\omega_0)^2 \cong \frac{1}{Lcab.C1}$$

$$\therefore\ C1 = \frac{1}{Lcab.(\omega_0)^2}$$

yielding C1 as approximately {1/[7.187u.(2.π.10e+3)^2]} = 35.24 uF

To allow optimal damping, it was decided to add a resistor in the same branch as the selected C1 component. To calculate the optimum value of the damping resistor R1, note that

$$\mathrm{R1}_{opt} = \sqrt{\frac{\mathrm{Lcab}}{\mathrm{C1}}}$$

resulting in R1opt = {sqrt[7.187u/35.24u]} = sqrt[0.219] = 0.47Ω

An aluminum polymer cap with nominal capacitance of 33 uF and ESR of 11 mΩ was selected and series connected with a pulse-rated resistor R1 set to 470 mΩ. The simulation of **Figure 3(a)** was executed to produce the outcome in **Figure 3(b)**. Note that the peak of the transient is limited to 66V.

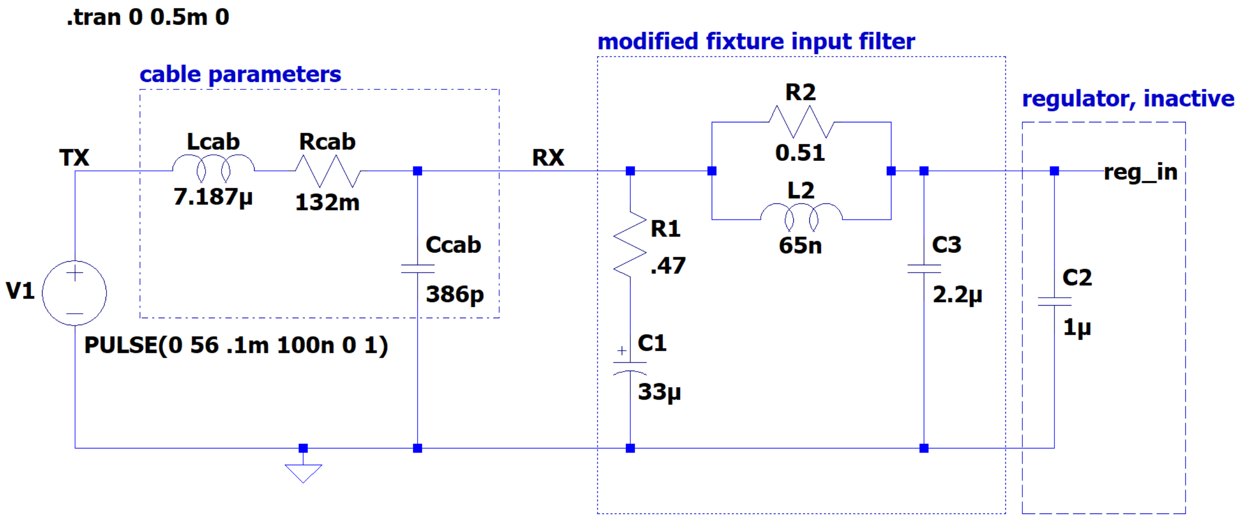


Figure 3(a) – inclusion of C1 and R1 to provide control of input turn-on OV transient.

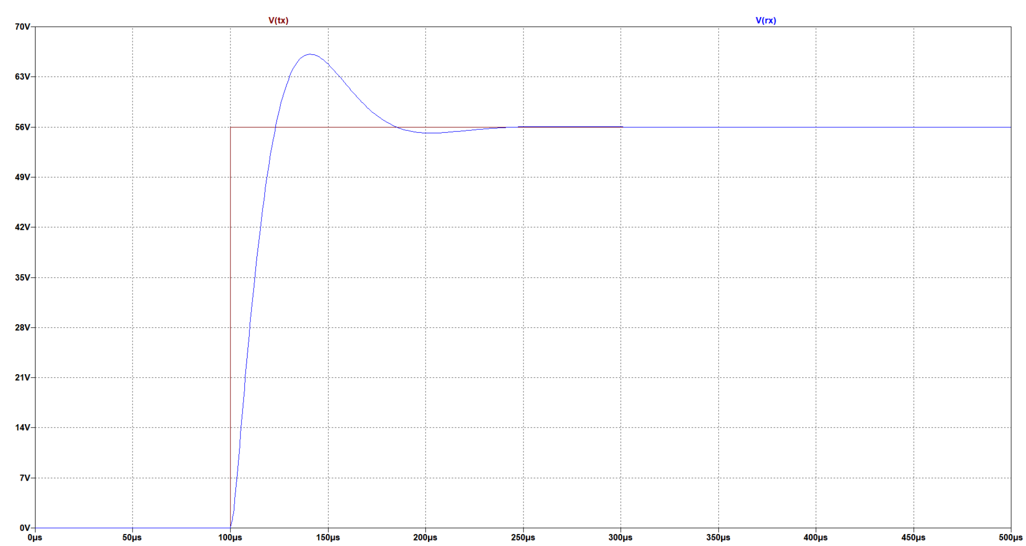


Figure 3(b) – outcome of simulation of modified fixture input filter showing optimally damped response.

If it can be so arranged, it is good practice to use slow rise-time DC sources when energizing “electrically long” tethers. A well-controlled source complemented with a regulator that has soft-start features helps avoid the development of such start-up transients.

SECOND APPLICATION· SAVING THE DAY AHEAD

As observed in the previous example, the cable has the ability under certain circumstances to ring or resonate. In the second case study, a DC source and a long umbilical is examined when a load pulse is generated at the RX end of the tether. The assumption is that the system is operating in the steady state, with active regulation of the load underway up to the point where the load pulse occurs. The interaction of two systems, the DC bus and the regulator, at their shared interface, can be assessed using Middlebrook’s stability theorem. This invokes a frequency domain approach to problem solving.

The customer analyzed a system of high input voltage DC modules set aboard an AUV (autonomous underwater vehicle). A 500m long tether would be fed with 300V DC to carry 1.5 kW to loads on a mobile submersible platform.

Many specially made tethers include information about power conductor resistance, wire gauge, and geometry. Luckily, the specification sheet for the umbilical contained additional information: distributed parameters for the cabling. If these parameters aren’t available, they can be measured or estimated if the insulating materials, cable cross sections, and the physical arrangement of the conductors are known.

FREQUENCY DOMAIN MODELING

The steady-state AC model consists of the regulator, filtering, cabling, and the source’s local impedance. This can be used to assess the propensity of the system to exhibit significant transient behavior using frequency domain analysis.

The regulator is modeled as a negative resistor, simply because it is providing constant power to the load independently of the input voltage as defined by the regulator’s continuous input voltage range. If input voltage increases, the input current drops. Considering the case of lowering applied input voltage, the input current increases under this negative resistance law. This is opposite behavior exhibited by a “positive” resistor in which current and voltage are proportional and in-phase with each other.

It is easy to calculate the negative resistance value. Maximum power draw at the load is 1.5 kW. With the converter U1’s efficiency being 95%, we use the input voltage and associated current figures to determine a worst-case (lowest) negative input resistance of the regulator. An alternative form of input impedance can be expressed as a change in input voltage for a given change in input current. Whichever is the lowest should be used.

The worst-case input impedance can be written as a formula like this

$$R = -\frac{Vin\_min^2}{Pin\_max}$$

The difference equation could also be used with

$$R = -\frac{\Delta Vin}{\Delta Iin}$$

With Vin being DC input voltage and Pin being input power, ΔVin is the change in input voltage for a corresponding change in input current ΔIin.

With Pout_max being maximum output power and η the corresponding efficiency, input power Pin_max is given by

$$Pin\_\mathrm{max} = \frac{Pout\_max}{\eta}$$

We find that Pin_max = 1.58 kW from which R = -(300)^2/1580 = -57 Ω. Magnitude of the regulator input impedance | Z_{reg_in} | translates to 20.[$\log_{10}$ 57] = 35.12 dB normalized to 1Ω.

By establishing the ratio of driving point voltage to current, we can find the input impedance of the regulator and the output impedance observed by the regulator. Note that because the current source {I1 or I2} is set to 1A in each circuit of **Figure 4(a)**, the impedance magnitudes V(d_c_RX) and V(rx) are plotted in decibels, along with the regulator impedance of 35.12 dB.

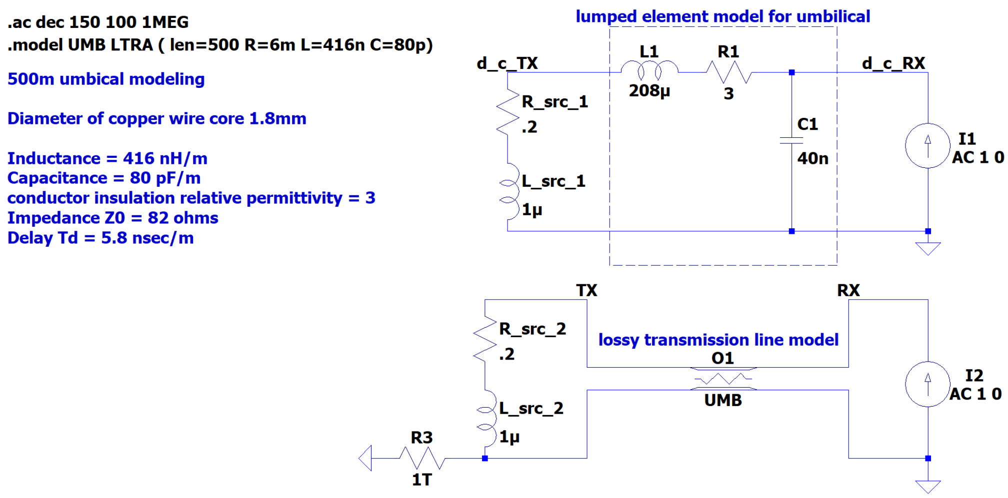


Figure 4(a) – tethered UAV lumped element and transmission line models in the frequency domain. The red arrows indicate the source impedance outcomes illustrated in figure 4(b).

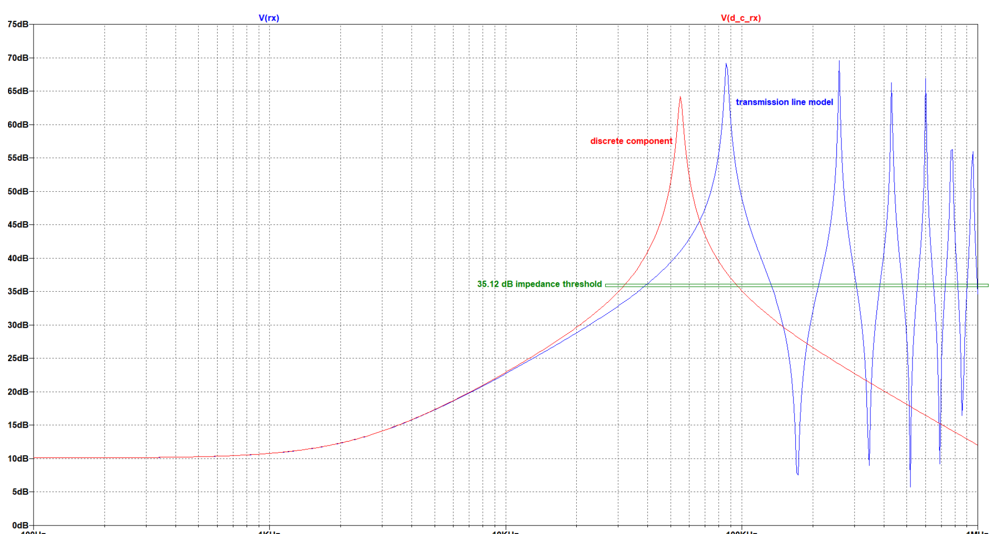


Figure 4(b) – lumped (discrete component) and distributed (transmission line) power bus source impedances observed by the driving CC sources I1 or I2.

To prevent unstable interaction between the bus and the converter, Middlebrook's stability criterion stipulates that the impedance Z_{SOURCE}, observed from the RX power port back toward the TX port, must have a magnitude which is a tenth or less than the regulator's own internal AC input impedance Z_{REG_IN}

$$Z_{SOURCE} \leq \frac{Z_{REG\_IN}}{10}$$

Both impedance outcomes in **Figure 4(b)** show that the bus impedances fail to meet the Middlebrook criterion. The lumped element circuit exhibits a single impedance peak. The lossy transmission line model exhibits a series of peaks, showing very wide variations in the observed impedance toward the source that occur throughout the frequency domain, corresponding with multiple resonances. Clearly this behavior isn't desirable in a power tether!

The problem-solving approach that we will adopt is straightforward. The placement of a single "lossy" capacitor served to resolve the OV problem in the first case study. Will it resolve the failure of the system in this case if it is included?

Having determined the input impedance of the regulator, we can now add it to the right-hand side of all the other elements, along with the lossy cap. The stabilized bus schematics and simulation outcomes are shown in **Figures 5(a)** and **5(b)**, respectively, with C1 capacitor damping set to 3 different values. The DC source inductance and resistance that were shown in **Figure 4(a)** have been discounted, as they are very small compared with L1 and R1. They are also removed in the corresponding TL schematics.

Figures 6(a) and **6(b)** show a time-domain simulation and matching response outcome for each cable model, based on setting the damping resistor in the lossy capacitor branch to 1.56 Ω.

Comparing the LE and TL model bus impedance plots, a correctly damped lossy capacitor has the effect of "masking" the transmission line (as seen in the blue traces in **Figure 5(b)**. Its presence dominates the source/bus impedance. The LE and TL bus-modelled impedances "converge" in the presence of the lossy capacitor. The regulator is now paralleled with about 1/10th of its own input impedance. Time domain responses in **Figure 6** confirm bus stability.

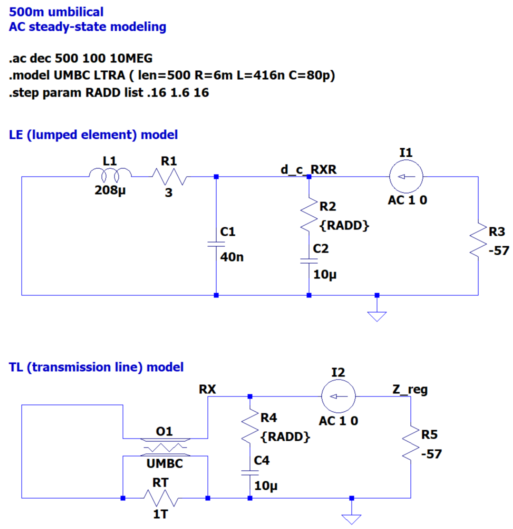


Figure 5(a) – frequency domain LE and TL modelled stability in tethered UAV.

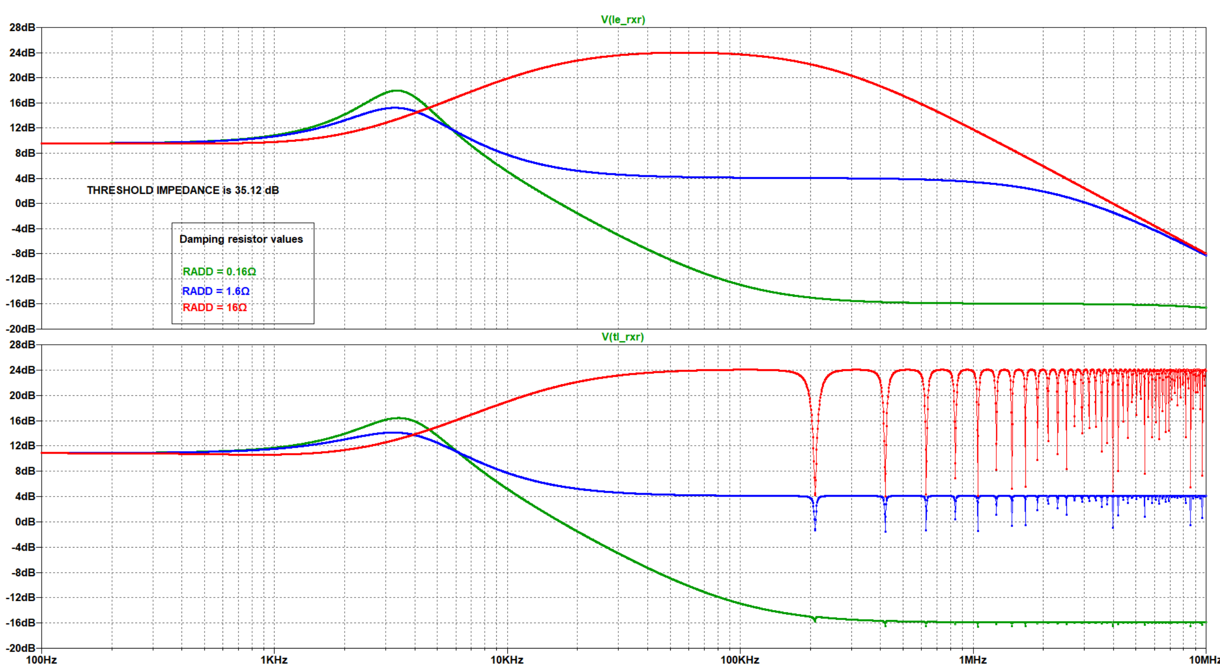
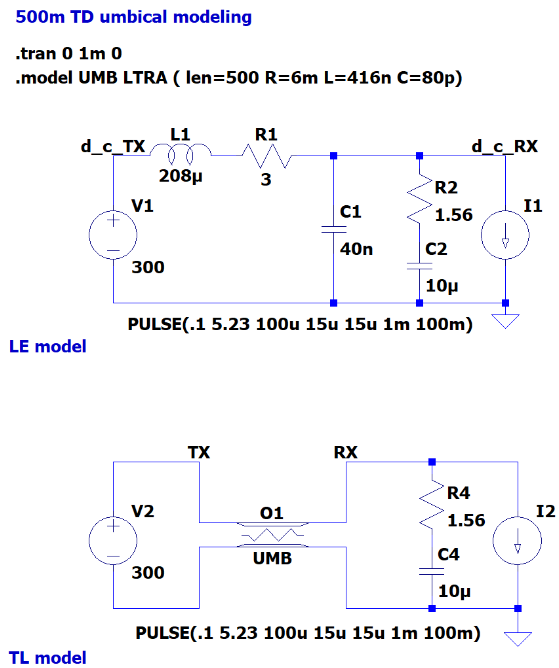


Figure 5(b) – effect of setting RADD to various values in the discrete circuit representation on SM (stability margin).



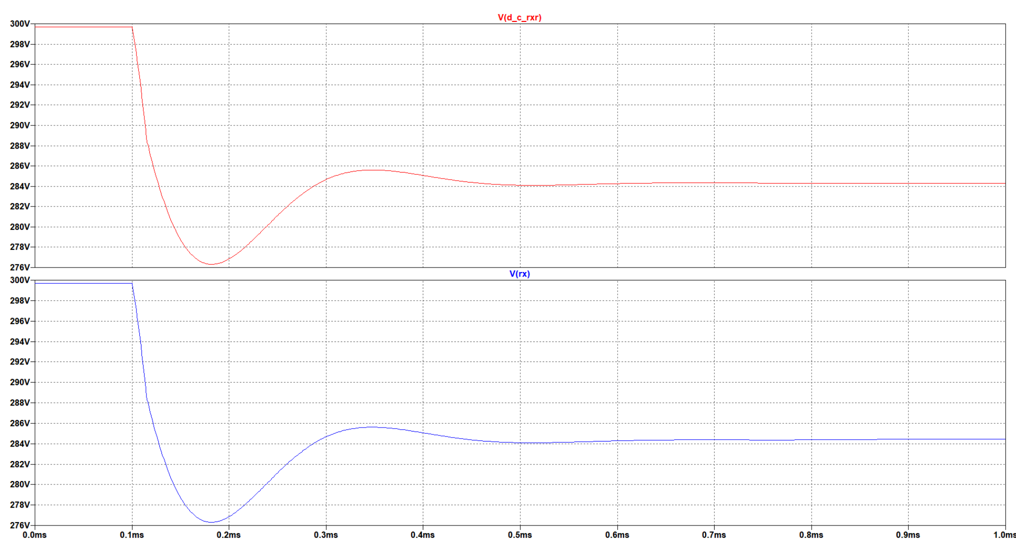


Figure 6(b) – TD simulation outcomes are almost the same for optimally damped LE and TL models.

SUMMARY

Case studies have been presented for systems in which long tethers are used for point-to-point connection of remotely located source and load. These examples highlight the need for and methods of modeling which supports the design of power systems using long cables for powering remote systems.

Irrespective of the model that might be used for analyzing the tether system, adequate decoupling at the regulator leads to a consistent stable operating solution which is no longer dependent on the tether itself.

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David joined AstrodyneTDI in July of 2021 as the Field Application Engineer based in the UK supporting all of Europe. Previously, he was with Vicor (UK), where he covered Western and Central Europe. He has worked in similar roles with Analog Devices, National Semiconductor, Micrel Semiconductor, and Vicor over a span of 26 years. He has a technical background underpinning the fields of RF, analogue mixed-mode, microwave, optics, and power electronics and DSP. David received his B.S. in Electrical and Electronic Engineering at the University of Bath UK. He attained M.Sc. and M.Phil. Degrees, specializing in analog IC design, at Southampton University UK with a MoD (RN) sponsored research assistantship. While working for Hughes Network Systems on satellite ground hardware systems, he studied for an advanced most Master's Certificate in Engineering at Johns Hopkins University in Maryland. He served as the University of Maryland, Baltimore County's 1st Professor of Practice in computer engineering, architect leading novel, and is a successful undergraduate CMPE capstone. He also developed programs and trained electronics technicians engaged in the defense and commercial sectors at various times in his 35-year career to date.

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